Simulation of Drifters in a Turbulent Ocean

Roland W. Garwood, Jr., Ramsey R. Harcourt, and Rebecca E. Stone
Naval Postgraduate School, Monterey, CA

Introduction

Why do the proverbial flotsam and jetsam collect into streaks and patches at the surface of the ocean? The same Oceanic Planetary Boundary Layer (OPBL) forces that organize debris and plankton blooms at the ocean surface influence all freely drifting objects, including man-made platforms and buoys. Our interest in the answer to this question comes from a variety of environmental and defense-related needs. This includes prediction of phytoplankton blooms, oil spill management, mine warfare, search and rescue, and oceanographic sensing with Lagrangian drifters (Figure 1), to name a few. On a time scale less than an hour, near-surface convection of heat can alter or destroy a sound channel. Episodic seasonal convection initiates the global-scale thermohaline circulation, and it may modify the ocean-atmosphere climate on time scales from decades to centuries. Hence, advancement in the understanding and prediction of convection is important for predictions ranging from tactical sonar to climate and global change. In this brief article, we show computer predictions that illustrate how convection has special effects upon freely drifting material at all depths of the OPBL.

Large-Eddy Simulation of Convection

At the OPBL Laboratory of the Naval Postgraduate School, the opening question has been addressed with the specific purpose of understanding the motion and response of oceanographic sensor systems aboard instrumented floats. These floats have been released into the Labrador Sea as part of the Office of Naval Research Accelerated Initiative on Deep Oceanic Convection. The ultimate goal of this multi-institutional initiative is to learn to represent realistically turbulent processes and the thermodynamic consequences of convection in prediction models for ocean temperature, salinity and velocity. In addition to traditional shipboard Eulerian oceanographic and atmospheric observations, Lagrangian and semi-Lagrangian observations are made by drifting packages of instruments.

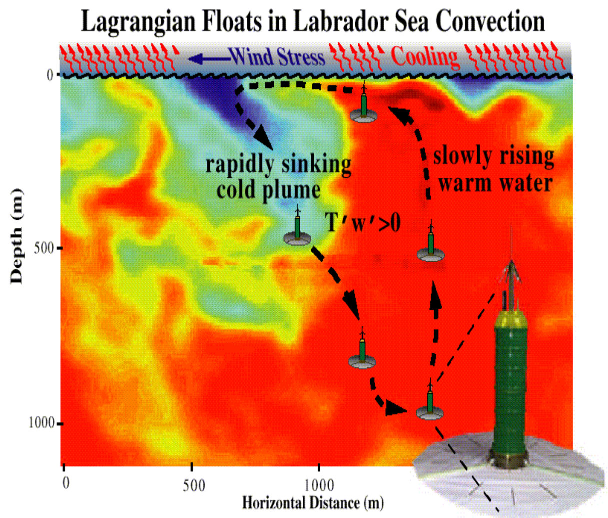

Figure 1. Schematic diagram of Lagrangian drifters [1] in LES-predicted OPBL turbulence. Drifters being carried by the convection have a one square meter cross sectional are and are not to scale. Such drifters are ideally suited for sensing the heat flux caused by the covariance between temperature and vertical velocity, T'w'.

Scientific interpretation of the observations of temperature and velocity from these drifters depends upon possible biases caused by the drifter motion. If a drifter behaves as a parcel of water and follows the water parcel trajectory, then it is purely Lagrangian. One of the drifter types used in the Labrador Sea was designed to be nearly Lagrangian [1]. If a drifter is designed to stay at a fixed depth but is free to be carried in any horizontal direction, then we term this drifter “isobaric.” Two different drifter types with semi-Lagrangian isobaric designs were deployed in the Labrador Sea experiment. The RAFOS float [2] is fixed-depth, with passive ballasting. The profiling ALACE floats [3] have programmable ballasting, allowing both isobaric and profiling modes. Because all drifters are designed with either a passive or active ballasting mechanism, and a finite-sized drifter can only approximate the motion of a water parcel, no drifter is either purely Lagrangian or exactly isobaric. One objective of the OPBL Laboratory is to use computer simulation to demonstrate the consequences of different ballasting and drag designs. This leads to better understanding drifter behavior and possibly to optimize the sensor mix and deployment strategies to meet the observational goals.

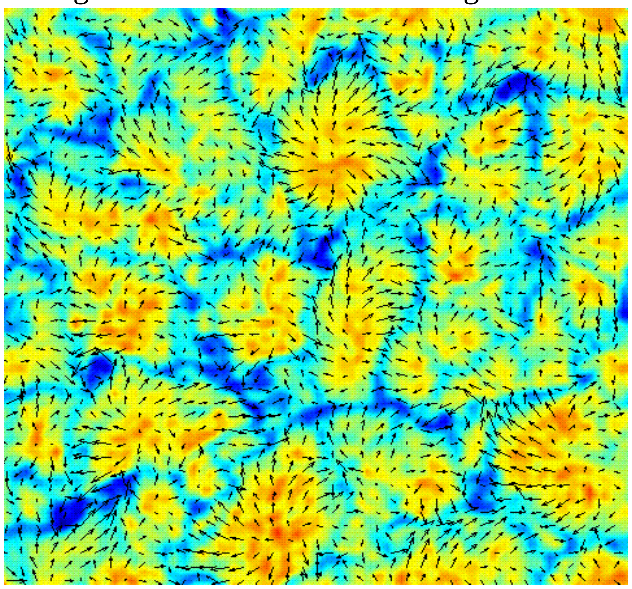

Figure 2. Surface temperature and Raleigh-Benard (R-B) circulation pattern associated with predominantly-free convection from a strong 400 w/ m^2 surface heat flux and light wind stress of 0.02 N/m^2 (caused by 3 m/sec winds). The horizontal scale of the largest R-B cells is similar to the depth (h) of the OPBL, which is 2 km in this case. The region shown is 6 km on each side.

Computer prediction of the time-dependent three-dimensional flow fields of the OPBL are provided by a Large-Eddy Simulation (LES) model [3,4,9]. Gridded temperature, salinity, velocity and pressure may be archived or used concurrently with the LES computations to predict motion of Lagrangian Drifter Models (LDM's) for the different drifter designs. Before showing the response of the LDM's, however, it is best to examine the variety of flow features that occur in the OPBL, in anticipation of the effects of organized turbulence structures upon drifting material.

LES results show that either free (Figure 2) or forced convection (Figure 3) may dominate, depending upon the magnitudes of surface heat flux, wind stress, and OPBL depth. Free convection predominates in the winter regimes of the subpolar and polar seas, especially in the very deeply convecting open water adjacent to marginal ice zones. In Figure 2, the wind stress is relatively light, so the buoyancy-driven Raleigh-Benard (R-B) cells tend to be radially symmetrical. These R-B cells consist of warmer water that rises from depth to the surface. This water is displaced upward by the rapidly descending plumes of surface-cooled water that originate in the cooler and more dense water between the R-B cells. Energy to drive the sinking plumes, and in turn the R-B circulation, is derived from the buoyancy flux associated with the release of heat and radiation to the atmosphere. The speed of the descending plumes (w) may be several cm/sec. The approximate diameter of the R-B cells scales with the depth (h) of the OPBL, which may vary from 10's of meters to more than a kilometer.

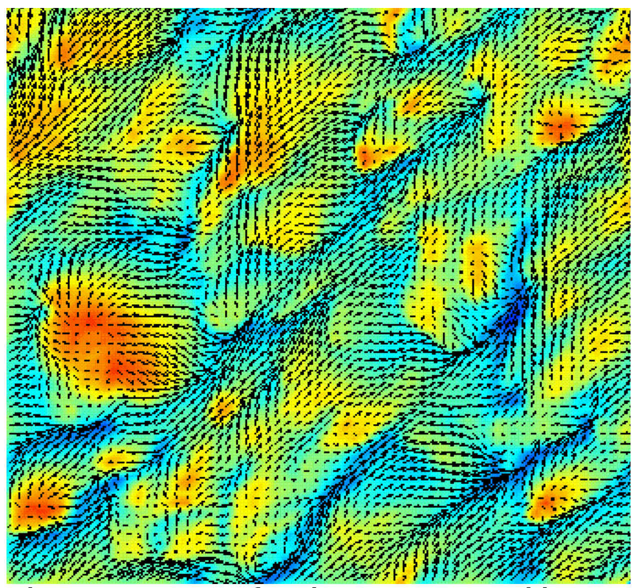

Figure 3. Same as for Figure 2, except with a strong wind stress in the y-direction of 1.0 N/ m^2 (caused by 20 m/sec winds). Horizontal rolls cause very strong convergence lines that lie about 45 degrees to the right of the wind.

As the OPBL deepens due to the accumulated effects of storm mixing and seasonal cooling, the vertical overturning time scale (h/w) of the free convection increases to become comparable to the inertial period (order 1 day). Then Coriolis force increasingly causes the R-B cells to rotate clockwise (northern hemisphere), as the flow diverges horizontally. This rotation and the natural unsteadiness of the turbulence prevent the R-B cells from assuming the classical hexagonal pattern of steady-state nonrotating free convection. Any drifting bodies and material floating on the surface will tend to be collected in the convergence zones between the R-B cells.

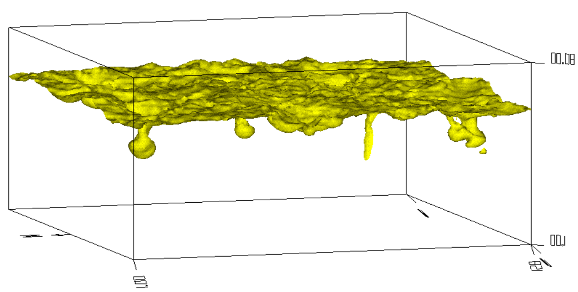

Figure 4. A temperature isosurface marks the lower boundary of a 200-m deep OPBL in this 3-D picture, with the horizontal dimensions being 1.5 km on a side. A number of thermobarically unstable plumes extend below the OPBL by 50 m to 150 m.

Forced convection is more important during the autumn storm forcing of temperate and subpolar seas, with mixing driven by kinetic energy from the wind. In Figure 3, a strong wind stress accompanies the surface cooling and sets up a circulation having extended convergence lines that lie in a direction approximately 45 degrees to the right of the wind stress direction. Because of the Coriolis force, these convergence lines are the surface manifestation of sets of horizontal rolls with opposing rotational directions. R-B cells are still evident, but freely drifting material at the surface will tend to collect in convergence zones produced by the wind-driven circulation. Most commonly, forced convection and free convection occur together. In the polar seas, forced convection may be an important precursor to free convection. The organized rolls of forced convection may help dilate a frazil ice field to create leads and enhance heat and buoyancy exchange between the OPBL and the atmosphere, helping to perpetuate deep convection [6].

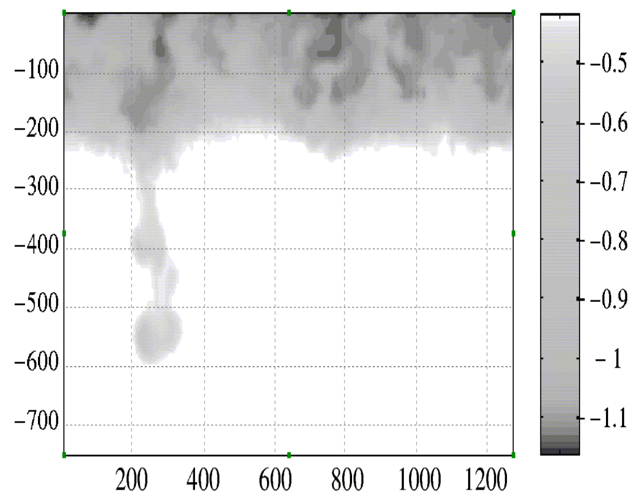

Figure 5. An x-z slice of the temperature field from the same simulation as for Figure 4, showing a single thermobaric plume that penetrates 400 m into the underlying stable water mass. Scales are in meters. The coldest water (shaded darkest) is colder than -1.1 C. The warmest water (white) is warmer than -0.4 C. In the polar seas, warmer water can under colder water because salinity dominates the density (low salinity in the OPBL and higher salinities below 200 m).

Yet another kind of organized cell structure is possible in the coldest and deepest oceanic convection - thermobaric conditional instabilities [7,4]. The term “thermobaric” refers to the nonlinear density effect of temperature and pressure together to increase the downward acceleration of sinking plumes of cold water. In normal convection, water parcels do not escape the OPBL. Rather, the turbulent OPBL deepens as it entrains the underlying nonturbulent stratified water. However, the unusual thermobaric plumes of the polar-sea OPBL may be detrained - escaping the OPBL much as cumulus clouds escape the atmospheric planetary boundary layer. Figure 4 shows an LES prediction of the onset of a field of thermobaric conditional instabilities in the Greenland Sea [8]. In Figure 5, a single plume extends 400 m into the otherwise stable and nonturbulent layers beneath a 200-m deep OPBL. With mass escaping the OPBL, the depth of the OPBL may decrease - in opposition to the tendency of the

OPBL depth to increase by entrainment. Lagrangian drifters and particulate matter trapped in such conditionally unstable plumes may be carried downward below the OPBL with speeds of possibly hundreds of m/hr - perhaps the highest vertical ocean current velocities on earth. As a corollary, drifters residing in the underlying stable water being penetrated by the conditionally unstable plumes will rise slowly because of water mass conservation.

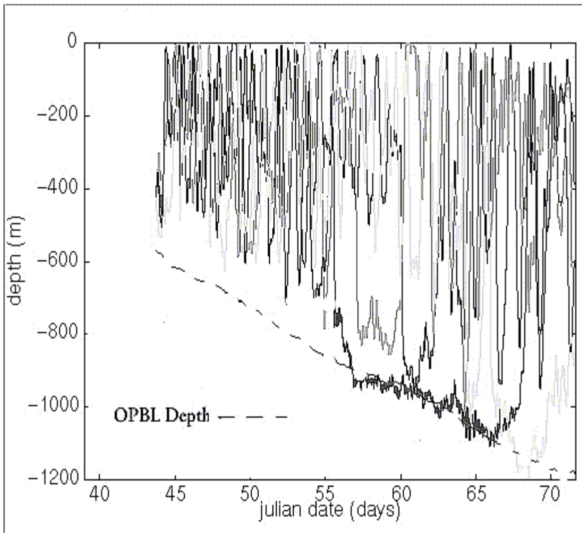

Figure 6. An ensemble of time-dependent depth records for Lagrangian drifters in the 28-day prediction of the 1997 wintertime convection of the Labrador Sea. The dashed line is an analysis of the OPBL depth for the period. These purely Lagrangian drifters repeatedly circulate from the surface to the bottom of the OPBL.

Simulation of Drifters in a Convective Ocean

With pre-computed LES velocity, pressure, temperature and salinity fields, Lagrangian and isobaric drifter motion and sensor response may be predicted iteratively, Figures 6 and 7 respectively. The turbulent kinetic energy (TKE) and turbulent fluxes of heat, mass and momentum detected by these LDM's are evaluated and compared with the Eulerian calculations (gridded data) from the numerical experiments. The numerical results indicate that Lagrangian drifters can potentially resolve well the TKE, the heat flux, as well as nutrient and other tracer fluxes.

Lagrangian drifters are also able to define the time-dependent vertical and horizontal scales of the convecting plumes. Observations of velocity and temperature by purely Lagrangian drifters will not be biased. However, actual drifters will not always perform ideally, and realistic LDM's for these drifters are being constructed which will assist in the analysis of the field data provided by these drifters. In Figure 6, one of the idealized and unbiased Lagrangian drifters was temporarily detrained from the OPBL and later re-entrained. This may not happen with real LDM's that will have a small positive buoyancy when in the lower reaches of the OPBL.

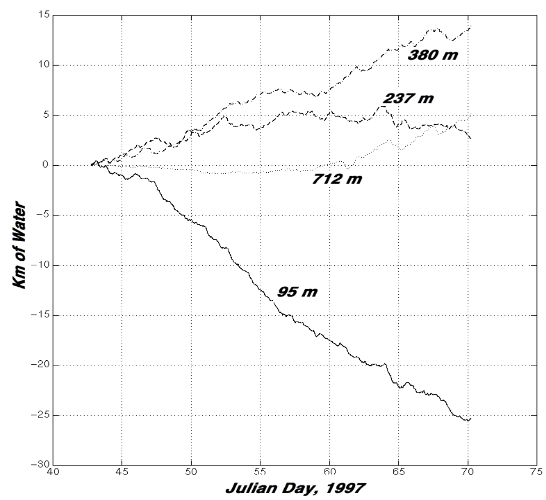

Figure 7. The time-integrated vertical velocity of four isobaric drifters, simulated for the same period as for Figure 6. The drifter most near the surface (95 m) experiences a strong downward mean velocity of more than 1 cm/sec, resulting in an apparent vertical displacement of more than 25 km during the period. The isobaric drifter at 380-m tends to lie in convergence zones having a mean downward velocity of about 0.7 cm/sec. The drifter at 237 m experiences an upwelling before about day 60, and then a downwelling after day 60 as the OPBL deepens below 1 km.

Compared with the Lagrangian drifters, the isobaric drifters' sampling statistics are biased. The isobaric drifters will sense mean fields for temperature and velocity that will be biased by the tendency for the fixed-depth drifters to seek out and maintain position in zones of horizontal convergence. Depending upon the ballasting depth, these drifters will experience a significant mean vertical velocity that is caused by the turbulence, not by a true mean upwelling/downwelling. Figure 7 shows that nearly 15 km of water is advected vertically upward past an isobaric drifter simulated to be ballasted to drift at the 380-m depth during 28 days of simulated Labrador Sea convection during February-March 1997. In the same simulation, more than 25 km of water is advected downward past a drifter at the 95-m depth. Depending upon the drifter's relative position within the OPBL, the vertical current may be either downward, if in the upper regions, or upward, if in the lower regions. Isobaric drifters should be particularly useful for tracking more energetic convective plumes. The isobaric drifters are also more likely to observe significant events and maximum-likely vertical velocity. Experimentally, a combination of Lagrangian and isobaric drifters may be best both to track convection and to measure accurately the fluxes.

In closing, insight into optimal drifter sampling strategies might be gained by considering the behavior of marine organisms. Do plankton and higher marine organisms use convection to enhance survivability? Tracers or neutrally buoyant and passive organisms will be advected like Lagrangian drifters, with effective diffusion and dispersion rates well simulated by the Lagrangian drifter results here. However, like the isobaric drifters in Figure 6, organisms that maintain a particular depth in the upper third of the OPBL, either by ballasting or by swimming, will statistically experience a large mean downwelling. Similar isobaric organisms in the lower two-thirds of the layer may experience a large upwelling. By maintaining a nearly fixed depth, such organisms should experience a continual vertical current with flow speeds as large as hundreds of meters per day, depending upon the surface forcing. Other organisms may "ride" the vertical currents as pure Lagrangian drifters, possibly extending their vertical range advantageously. These simulations provide some new insight into the response of typical drifters to convective oceanic flow fields, and they are a basis for future simulation of turbulent advection of drifters - both man-made and natural.

Acknowledgments

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Biographies

Roland Garwood received a BS in Electrical Engineering from Bucknell University in 1967. He received a Ph.D. in Oceanography from the University of Washington in 1976, after serving as a NOAA commissioned officer from 1968-71. He joined the faculty of the Naval Postgraduate school's Department of Oceanography in 1976, specializing in ocean dynamics and air-sea interactions. Ramsey Harcourt is a research assistant in the Department of Oceanography at the Naval Postgraduate School. He received a Masters in Physics from the University of California at Santa Cruz in 1991. His primary interest is Large Eddy Simulation of the ocean turbulent boundary layer, and he is currently writing a Ph.D. dissertation on the behavior of drifters in open ocean deep convection. Lieutenant Commander Stone was commissioned in the U.S. Navy in 1985; after a shipboard tour, she became a Navy Oceanographer, serving in Washington, D.C. and in Guam. She received both Masters degrees in Meteorology and Physical Oceanography from the Naval Postgraduate School, where she is a doctoral candidate.

References

1. D'Asaro, E. A., A Lagrangian float, J. Atmos. Oceanic Technol., 13, 1230-1246, 1996.

2. Rossby, T., D. Dorson, and J. Fontaine, The RAFOS system, J. Atmos. Oceanic Technol., 3, 672-679, 1986.

3. Davis, R. E., D. C. Webb, L. A. Regier, and J. Dufour, The autonomous Lagrangian cir-

culation explorer (ALACE), J. Atmos. Oceanic Technol., 9, 264-285, 1992.

4. Garwood, R. W., Jr., S. M. Isakari and P. C. Gallacher, Thermobaric convection, in The Role of the Polar Oceans in Shaping the Global Environment, Ed. by O. Johannessen, R. Muench and J. Overland, Am. Geophys. Union Monograph, Vol. 85, 199-209.

5. Harcourt, R. R., L. Jiang, and R. W. Garwood, Jr., Numerical simulation of drifter response to Labrador Sea convection, Tech. Rep. NPS-OC-98-001, Naval Postgraduate School, Monterey, 71 pp., 1998.

6. Carsey, F. D. and R. W. Garwood, Jr., Identification of modeled ocean plumes in Greenland Gyre ERS-1 SAR data, Geophys. Res. Lett., 20, 2207-2210, 1993.

7. Garwood, R. W., Jr., Enhancements to deep turbulent entrainment, In Deep Convection and Deep Water Formation in the Oceans, Ed. by P. C. Chu and J. C. Gascard, 197-213, 1991.

8. Stone, R. E., Deep mixed layer entrainment, MS thesis, Naval Postgraduate School, Monterey, 67 pp., March 1997.

9. http://www.oc.nps.navy.mil/opbl is the OPBL Laboratory home page.